

Sub-GeV flashes in γ -ray burst afterglows as probes of underlying bright far-ultraviolet flares

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ABSTRACT

Bright optical and X-ray flares have been observed in many Gamma-ray Burst (GRB) afterglows. These flares have been attributed to late activity of the central engine. In most cases the peak energy is not known and it is possible and even likely that there is a significant far-ultraviolet component. These far-ultraviolet photons escape our detection because they are absorbed by the neutral hydrogen before reaching Earth. However, these photons cross the blast wave produced by the ejecta that have powered the initial GRB. They can be inverse Compton upscattered by hot electrons within this blast wave. This process will produce a strong sub-GeV flare that follows the high energy (soft X-ray) tail of the far-UV flare but lasts much longer and can be detected by the upcoming *Gamma-Ray Large Area Telescope* (GLAST) satellite. This signature can be used to probe the spectrum of the underlying far-ultraviolet flare. The extra cooling produced by this inverse Compton process can lower the X-ray emissivity of the forward shock and explain the unexpected low early X-ray flux seen in many GRBs.

Key words: Gamma Rays: bursts—ISM: jets and outflows—radiation mechanisms: nonthermal—X-rays: general

1 INTRODUCTION

The XRT on board of *Swift* detected, during the last year, numerous X-ray flares in GRB afterglows (Burrows et al. 2005; Nousek et al. 2006; Goad et al. 2006; Romano et al. 2006; Falcone et al. 2006; O’Brien et al. 2006). These observations confirmed earlier findings of BeppoSAX (Piro et al. 1998, 2005; Galli & Piro 2006; in’t Zand et al. 2004) and ASCA (Yoshida et al., 1999). These flares have been interpreted as arising from late time activity of the central engine (King et al. 2005; Perna et al. 2006 and Proga & Zhang 2006) producing either internal shocks (Fan & Wei 2005; Zhang et al. 2006; Zou, Xu & Dai 2006; Wu et al. 2006) or internal magnetic dissipation (Fan, Zhang & Proga 2005a).

The flare detected in the afterglow of GRB 050502b peaks in the soft X-rays (Falcone et al. 2006). However, the peak energy of most flares is unknown (B. Zhang, 2006, private communication). It is possible, and even likely, that a significant fraction of the energy or even most of it is emitted in the far-ultraviolet (FUV) band. For example in the

internal energy dissipation model the typical synchrotron radiation frequency depends sensitively on the physical parameters (Fan & Wei 2005; Zhang et al. 2006; Fan et al. 2005a) and the synchrotron self-absorption frequency is $\sim 10^{15}$ Hz (Fan & Wei 2005). It is possible, therefore, that the observed X-ray flares are the high energy tails of FUV flares. It is also possible that there are FUV flares that have not been detected at all. Further support for this idea arises from the possible interpretation of the optical flare seen in GRB 050904 (Böer et al. 2006) as a late time activity of the inner engine (Wei, Yan & Fan 2006).

Even if FUV flares exist they won’t be observed as the FUV photons are absorbed by the neutral hydrogen in the GRB host galaxy as well as in our Galaxy. We show here that an underlying FUV flare will be upscattered and produce (after inverse Compton) a sub-GeV flare that may be detected by the upcoming *Gamma-Ray Large Area Telescope* (GLAST; see <http://glast.gsfc.nasa.gov/>) satellite. Though (sub-)GeV flashes in GRB afterglows could arise in other scenarios (e.g., Mészáros & Rees 1994; Plaga 1995; Granot & Guetta 2003; Dermer & Atoyan 2004; Beleborodov 2005; Fan, Zhang & Wei 2005b), the high energy photon flashes predicted in this Letter can be distinguished easily since they

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follows the high energy (soft X-ray) tail of the FUV flares (see also Wang, Li & Mészáros 2006), which is unexpected in any alternative model. Our prediction could be tested by the cooperation of *Swift* and GLAST. This is possible as *Swift* XRT usually slews to the GRB source in ~ 100 seconds and, the field of view of the GLAST burst monitor (GBM) is all sky not occulted by the earth and the Large Area Telescope (LAT) will slew to the GRB direction automatically in ~ 5 minutes.

2 THE PHYSICAL MODEL

The physical process is as follows: A few minutes after the end of the prompt γ -ray emission, the central engine becomes active again and this renewed activity gives rise (either via internal shocks or via magnetic dissipation) to a strong FUV flare. At this time the original ejecta that has produced the GRB has propagated into the circum-burst matter. The blast waves obtained a Blandford-McKee profile with a strong shock wave in its front (see Fig. 1). The flare FUV photons cannot be detected on earth as they are absorbed by the neutral Hydrogen. However, its high energy (soft X-ray) tail might be seen. As the FUV photons catch up with the blast wave they cool the shock heated electrons through external inverse Compton (EIC) scattering. A very small fraction of the FUV photons is boosted to a much higher frequency, typically in sub-GeV range. This can be observed as a sub-GeV flare.

The basic mechanism is radiation produced inside the ejecta at a small radius is Comptonized in the external blast wave at a much larger radius. Beloborodov (2005) considered, first, this effect for Comptonization of prompt 100 keV photons in the reverse shock of the blast wave. The Comptonization of the prompt photons in the forward shock was investigated by Fan et al. (2005b). Wang et al. (2006) considered a scenario in which X-ray photons from X-ray flares are upscattered to GeV and higher energies. However, as we discuss later the observed X-ray flare fluxes may be too low to produce a significant observable GeV signal. FUV flares, that we discuss here, are motivated by the very soft spectrum of the observed X-ray flares. Their fluence is not constrained by current observations and the sub-GeV flare that we predict is the only way known to explore their existence. Furthermore, as we show below, a FUV fluence comparable to the fluence of current X-ray flares will produce a signal that can be observed by GLAST

We focus on the FUV flares taking place at 100 – 1000 seconds after the burst since (i) γ_m decreases rapidly with time. At later times, the scattered photons are not in the high energy range. (ii) The early FUV flares are relatively energetic and contain more seed photons.

For our purpose the total number of seed photons (rather than the total energy) is more important as this determine the total number of high energy (upscattered) photons. To obtain a reliable estimate of the number of detected photons we need to calculate the probability of up-scattered of a seed photon by the forward shock electrons, i.e., the optical depth of these electrons (§2.1). We also need to estimate the number of the flare photons (§2.3). A simple

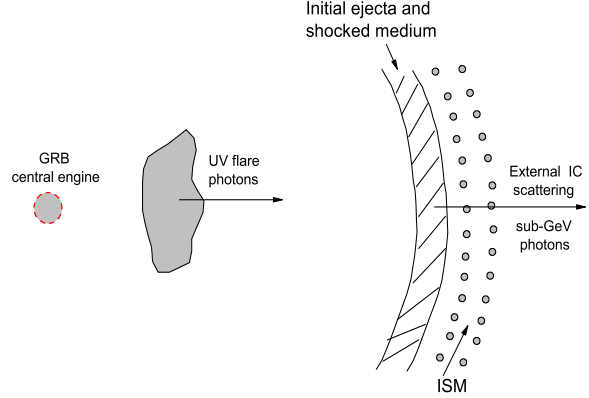


Figure 1. A schematic cartoon of the flare photons—external forward shock electrons interaction.

estimate of these factors yields, for an ISM surrounding:

$$\begin{aligned} N_{\text{obs}} &\approx \sigma_T n_0 (R/3) \frac{\mathcal{F}}{h\nu_{uv}} S \\ &\approx 10n_0 R_{17} \mathcal{F}_{-6} (\nu_{uv}/0.01\text{keV})^{-1} (S_{\text{GLAST}}/8000\text{cm}^2), \end{aligned}$$

where R is the radius of the forward shock, n_0 the surrounding density, \mathcal{F} is the fluence of the seed FUV photons' flare and ν_{uv} is their typical frequency. S is the detectors area and $S_{\text{GLAST}} \sim 8000\text{cm}^2$ is the effective area of Large Area Telescope (LAT) onboard GLAST. Here and throughout this text, the convention $Q_x = Q/10^x$ has been adopted in cgs units. Later we elaborate on these estimates. We also need to take into account the important correction caused by the anisotropic emission of the scattered photons (in the comoving frame of the shocked material), which has been ignored previously (see eqs. (12-14) for details).

2.1 The optical depth

In the standard GRB afterglow model (e.g. Sari, Piran & Narayan 1998; Piran 1999) the blast wave propagates into a constant density ISM. In this case

$$\gamma_m \simeq 1.7 \times 10^3 \epsilon_{e,-1} C_p E_{k,53}^{1/8} n_0^{-1/8} t_3^{-3/8} [(1+z)/2]^{3/8}, \quad (1)$$

where E_k is the isotropic kinetic energy of the initial GRB outflow, $C_p \equiv 13(p-2)/[3(p-1)]$, $p \sim 2.3$ is the power-law index of the shocked electrons, t is the observer's timescale in units of second, z is the redshift of the burst, ϵ_e and ϵ_B represent the fractions of shock energy given to the electrons and magnetic field, respectively. The Lorentz factor of the cooling electrons is

$$\gamma_e \simeq 1.5 \times 10^4 E_{k,53}^{-3/8} \epsilon_{B,-2}^{-1} n_0^{-5/8} t_3^{1/8} [(1+z)/2]^{-1/8} (1+Y)^{-1}, \quad (2)$$

where Y is the Compton parameter, which is a sum of the synchrotron self-Compton (SSC) parameter Y_{SSC} and the EIC parameter Y_{EIC} . Following Fan & Piran (2006; see Appendix A), $Y_{\text{SSC}} \simeq \{-(1+Y_{\text{EIC}}) + \sqrt{(1+Y_{\text{EIC}})^2 + 4\eta\eta_{KN}\epsilon_e/\epsilon_B}\}/2$, where $\eta = \min\{1, (\gamma_m/\gamma_e)^{(p-2)}\}$ (e.g. Sari, Narayan & Piran 1996). The coefficient $0 \leq \eta_{KN} \leq 1$ accounts for the Klein-Nishina effect. For $\bar{\gamma}_e = \min\{\gamma_e, \gamma_m\} \sim 10^3$, $\eta_{KN} \sim 1$ (see Appendix B. of Fan & Piran 2006). To get γ_e , we also need to estimate the parameter Y_{EIC} .

In the shock front, the magnetic energy density can be estimated as

$$U_B \simeq 0.1 \text{ ergs cm}^{-3} \epsilon_{B,-2} E_{k,53}^{1/4} n_0^{3/4} t_3^{-3/4} [(1+z)/2]^{3/4}. \quad (3)$$

At t , the forward shock front reaches the radius $R \simeq 1.9 \times 10^{17} \text{ cm}$ $E_{k,53}^{1/4} n_0^{-1/4} t_3^{1/4} [(1+z)/2]^{-1/4}$. In the forward shock region, the energy density of FUV photons of the flare can be estimated as

$$\begin{aligned} U_{ph} &\simeq \frac{L_{ph}}{4\pi R^2 \Gamma^2 c} \\ &= 0.4 \text{ ergs cm}^{-3} L_{ph,49} E_{k,53}^{-3/4} n_0^{3/4} t_3^{1/4} \left(\frac{1+z}{2}\right)^{-1/4}, \quad (4) \end{aligned}$$

where L_{ph} is the luminosity of the flare. Note that the flare lasts $\Delta T (< t)$. Its contribution to the cooling of the electrons can be estimated by the EIC parameter

$$\begin{aligned} Y_{EIC} &\approx (\Delta T/t)(U_{ph}/U_B) \\ &\simeq 4(\Delta T/t) L_{ph,49} \epsilon_{B,-2}^{-1} E_{k,53}^{-1} t_3 [(1+z)/2]^{-1}. \quad (5) \end{aligned}$$

Provided that $\Delta T/t \sim 0.3$, $Y = Y_{SSC} + Y_{EIC} \simeq 3$ for typical parameters and $\gamma_c \sim 4 \times 10^3$. We have $\bar{\gamma}_e = \min\{\gamma_m, \gamma_c\} \sim 2 \times 10^3$. These electrons scatter on the flare photons and boost them to the typical energy (in the observer frame)

$$h\nu_{\text{obs}} \sim 2\bar{\gamma}_e^2 h\nu_{\text{uv}} = 80 \text{ MeV } \bar{\gamma}_{e,3.3}^2 (h\nu_{\text{uv}}/0.01\text{keV}), \quad (6)$$

where h is Planck's constant and ν_{uv} is the typical initial photon frequency.

Obviously, the scattering is in the Thompson regime. The optical depth for a flare photon to be scattered can be estimated by

$$\tau_{\text{ISM}} \simeq \sigma_T n R / 3 \simeq 4.2 \times 10^{-8} E_{k,53}^{1/4} n_0^{3/4} t_3^{1/4} [(1+z)/2]^{-1/4}, \quad (7)$$

where σ_T is the Thompson cross section.

In the stellar wind model (Dai & Lu 1998; Mészáros, Rees & Wijers 1998), $n = 3 \times 10^{35} A_* R^{-2} \text{ cm}^{-3}$, where $A_* = [\dot{M}/10^{-5} M_\odot \text{ yr}^{-1}] [v_w/(10^8 \text{ cm s}^{-1})]$ (Chevalier & Li 2000), \dot{M} is the mass loss rate of the progenitor, v_w is the velocity of the wind. Now $\gamma_m \simeq 970 \epsilon_{e,-1} C_p E_{k,53}^{1/4} A_*^{-1/4} t_3^{-1/4} [(1+z)/2]^{1/4}$ and $\gamma_c \simeq 280 \epsilon_{B,-2}^{1/4} E_{k,53}^{1/4} A_*^{-5/4} t_3^{3/4} [(1+z)/2]^{-3/4} (1+Y)^{-1}$. Similar to the ISM case, at t the forward shock front reaches the radius $R \simeq 2.7 \times 10^{16} \text{ cm}$ $E_{k,53}^{1/2} A_*^{-1/2} t_3^{1/2} [(1+z)/2]^{-1/2}$, $U_B \simeq 13 \text{ ergs cm}^{-3} \epsilon_{B,-2} E_{k,53}^{-1/2} A_*^{3/2} t_3^{-3/2} (\frac{1+z}{2})^{3/2}$, $U_{ph} = 87 \text{ ergs cm}^{-3} L_{ph,49} E_{k,53}^{-3/2} A_*^{3/2} t_3^{-1/2} (\frac{1+z}{2})^{1/2}$, and the EIC parameter can be estimated by

$$Y_{EIC} \simeq 6.7 (\Delta T/t) \epsilon_{B,-2}^{-1} L_{ph,49} E_{k,53}^{-1} t_3 \left(\frac{1+z}{2}\right)^{-1}. \quad (8)$$

Provided that $\Delta T/t \sim 0.3$, we have $Y = Y_{SSC} + Y_{EIC} \simeq 3.4$ and $\gamma_c \sim 70$. So $\bar{\gamma}_e \sim 70$ for $t \sim 10^3 \text{ s}$. The possibility of one flare photon being scattered (i.e., the optical depth) can be estimated by

$$\tau_{\text{wind}} \simeq 7.3 \times 10^{-6} A_*^{3/2} E_{k,53}^{-1/2} t_3^{-1/2} [(1+z)/2]^{1/2}. \quad (9)$$

Now most scattered photons are in the sub MeV band and the count number is $\sim 0.05 \text{ cm}^{-2}$ (where eq. (11) and eq. (14) have been taken into account), which is undetectable for the *Swift* BAT. The tens MeV photons (resulting in the keV flare photons-forward shock electrons interaction) may be still detectable for the GLAST. But the counts rate is not

higher than that of the ISM case. On the other hand, there are just a small fraction of bursts were born in the stellar wind (e.g., Chevalier & Li 2000; Panaitescu & Kumar 2002). So we do not discuss this case further.

2.2 The duration of the high energy emission

As pointed out in Beloborodov (2005), the upscattered photons are de-collimated and their arrival time is affected by the spherical curvature of the blast wave. The duration of the high energy emission thus can be estimated as

$$T \sim \Delta T + (1+z)R/2\Gamma^2, \quad (10)$$

we have $T \sim 4t$ in the ISM case and $T \sim 2t$ in the wind case, which could be much longer than ΔT . The duration increases when the anisotropic radiation of the up-scattered photons (see eq. [13]) has been taken into account because now the strongest emission are from $\theta \sim 1/\Gamma$.

As a result, most of the up-scattered photons will arrive after the FUV flare. This lagging behavior is a signature of upscattering of internal radiation in the external blast wave, which may be tested by the observations.

2.3 The total number of soft photons

Assuming that the spectrum of the flare has the form $F_\nu \propto \nu^{-\beta_{XRT}}$ for $\nu > \nu_{\text{uv}}$, where $\beta_{XRT} \sim 1.2$, as reported in most X-ray flares (e.g. O'Brien et al. 2006). The total number of soft FUV photons reaching us (in unit area and without absorption) can be estimated by

$$N_{\text{tot}} \simeq \frac{\beta_{XRT} - 1}{\beta_{XRT}} \frac{\mathcal{F}}{h\nu_{\text{uv}}}, \quad (11)$$

where \mathcal{F} is the energy fluence of the flare.

2.4 The detectability of sub-GeV photons

The interaction between the photon beam and the isotropic relativistic electrons (i.e., the anisotropic IC scattering) has been discussed extensively (Brunetti 2001 and the references therein). Here the scattering is in the Thompson regime and the electrons are ultra-relativistic (their distribution is $n(\gamma_e) = K_e \gamma_e^{-\delta}$ for $\min\{\gamma_c, \gamma_m\} < \gamma_e < \max\{\gamma_c, \gamma_m\}$), the emissivity can be approximated as (i.e., eq. (43) of Brunetti 2001)

$$\begin{aligned} j(\cos \theta_s, \nu_s) &= K_e r_0^2 c \frac{(1 - \cos \theta_s)^{(\delta+1)/2} (\delta^2 + 4\delta + 11)}{(\delta+1)(\delta+3)(\delta+5)} \\ &\quad \nu_s^{-(\delta-1)/2} \int \nu^{(\delta-1)/2} n(\nu) d\nu, \quad (12) \end{aligned}$$

where $n(\nu)$ is the energy distribution of the seed photons, r_0 is the classic radius of the electron, θ_s is the scattering angle (measured in the comoving frame of the shocked material and set to zero on the line of the velocity vector), ν_s is the frequency of the scattered photon (measured in the comoving frame of the shocked material). As shown in eq. (12) the scattered power has a maximum at $\theta_s = \pi$ and goes to zero for small scattering angles. The shocked medium moves toward us with a bulk Lorentz factor about tens. The photons scattered in the comoving frame at an angle $\theta_s \sim \pi/2$ from the velocity vector are those making an

angle $\theta \sim 1/\Gamma$ with the line of sight in the observer frame $\cos \theta_s = (\cos \theta - \beta)/(1 - \beta \cos \theta)$. So the received power is depressed (relative to the isotropic seed photon case) but not significantly, as shown below.

If the seed photons are also isotropic (so are the scattered ones), integrating eq. (12) yields the well known result (e.g. Blumenthal & Gould 1970)

$$j(\nu_s) = \pi r_0^2 K_e c 2^{\delta+3} \frac{(\delta^2 + 4\delta + 11)}{(\delta + 1)(\delta + 3)^2(\delta + 5)} \nu_s^{-(\delta-1)/2} \int \nu^{(\delta-1)/2} n(\nu) d\nu. \quad (13)$$

What we care about is the divergency of receiving number of scattered photons at $\nu_{\text{obs}} = \mathcal{D}^{-1}\nu_s$ between the photon beam case and the isotropic photon case ($\mathcal{D} = \Gamma(1 - \beta \cos \theta)$ is the Doppler factor), which is represented by f_{cor} and can be estimated as (e.g. Rybicki & Lightman 1979)

$$f_{\text{cor}} \simeq \frac{\int_0^{\theta_j} j(\cos \theta_s, \mathcal{D}\nu_{\text{obs}}) \mathcal{D}^{-3} \sin \theta d\theta}{\int_0^{\theta_j} j(\mathcal{D}\nu_{\text{obs}}) \mathcal{D}^{-3} \sin \theta d\theta}, \quad (14)$$

where θ_j is the jet half-opening angle of the ejecta. We have $f_{\text{cor}} \simeq 0.4$ for $\delta \sim 2.3$ and $\theta_j \gg 1/\Gamma$.

In the ISM case,

$$N_{\text{obs}} \sim f_{\text{cor}} \tau_{\text{ISM}} N_{\text{tot}} S_{\text{GLAST}} = 1.3 C_\beta \mathcal{F}_{-6} \left(\frac{h\nu_{\text{uv}}}{0.01 \text{ keV}} \right)^{-1} E_{k,53}^{1/4} n_0^{3/4} t_3^{1/4} \left(\frac{1+z}{2} \right)^{-1/4}, \quad (15)$$

sub-GeV photons can be collected by GLAST, where $C_\beta \equiv 6(1 - \beta_{\text{XRT}})/\beta_{\text{XRT}}$. Usually at least five photos are needed to claim a detection (Zhang & Mészáros 2001), so we need $n \sim 10 \text{ cm}^{-3}$, which is typical (Panaiteescu & Kumar 2002).

The effective area of EGRET onboard Compton Gamma Ray Observatory (CGRO) is $S_{\text{EGRET}} \sim 1500 \text{ cm}^2$. A rather high circumburst density of $n \sim 100 \text{ cm}^{-3}$ is needed to get 5 sub-GeV photons. Afterglow modeling (Panaiteescu & Kumar 2002) suggests that such a high density is uncommon around GRB progenitors. They may be the reasons for the rare detections of delayed sub-GeV photon flashes by EGRET (see §3 for details).

Before turning to a comparison with observations we ask two questions. First we ask whether SSC process of the electrons accounting for the FUV flares can produce sub-GeV photons. We then ask what are the implications of the cooling due to the IC process on the forward shock emission.

The answer to the first question, can these sub-GeV photons be attributed to the SSC radiation of the electrons accounting for the FUV flares is very likely negative. Firstly, the outflow powering the FUV flares may be highly magnetized (Usov 1992; Thompson 1994; Lyutikov & Blandford 2003; Spruit, Daigne & Drenkhahn 2001; Fan et al. 2005a; Proga & Zhang 2006) in which case the synchrotron self-Compton radiation is too weak to be detectable. Secondly, if the late baryonic internal shock emission peaks in the FUV band (i.e., ν_{uv}), the typical SSC frequency should be $\sim \gamma_{e,m}^2 \nu_{\text{uv}} \sim 100 \text{ keV}$ $\gamma_{e,m,2}^2 (\nu_{\text{uv}}/0.01 \text{ keV}) \ll \text{tens MeV}$, where $\gamma_{e,m} \sim 100$ is the minimum Lorentz factor of electrons accelerated in the late internal shocks (see also Wei et al. 2006). Its contribution to sub-GeV emission flux is unimportant. If the typical synchrotron radiation frequency of late internal shocks is in X-ray band, the SSC radiation may peak in tens MeV band (Wang et al. 2006). However,

as we have already mentioned in section 1, for most “X-ray flares” detected so far, the peak energy may be lower than 0.2 keV. So the tens MeV emission from the SSC process may be infrequent.

We need to verify that the sub-GeV photons won’t be absorbed by the high energy tail of the FUV flare photons. The pair production optical depth for photons with energy $\sim 1 \text{ GeV}$ (absorbed by the flare photons with energy $\epsilon_{a,\text{obs}} \sim 2(\Gamma m_e c^2)^2 / [(1+z)^2 \text{ GeV}] \sim 0.2 \text{ MeV}$ $E_{k,53}^{1/4} n_0^{-1/4} t_3^{-3/4} [(1+z)/2]^{-5/4}$) can be estimated as (e.g., Svensson 1987)

$$\tau_{\gamma\gamma}(1 \text{ GeV}) \simeq \frac{11 \sigma_T N_{>\epsilon_{a,\text{obs}}}}{720 \pi R^2} \sim 10^{-5}, \quad (16)$$

where $N_{>\epsilon_{a,\text{obs}}} = \frac{\beta_{\text{XRT}}^{-1}}{\beta_{\text{XRT}}} \left(\frac{h\nu_{\text{uv}}}{\epsilon_{a,\text{obs}}} \right)^{\beta_{\text{XRT}}} \frac{4\pi D_L^2 \mathcal{F}}{(1+z)^2 h\nu_{\text{uv}}}$ is the total flare photon number satisfying $h\nu > \epsilon_{a,\text{obs}}$. Clearly such a small optical depth won’t affect the sub-GeV flux.

FUV flares may play an additional role. Consider the possibility that after the cease of the γ -ray burst, the central engine does not turn off and gives rise to long term but sharply decaying soft radiation component (mainly in far-ultraviolet band). The IC process of these FUV photons cools the forward shock electrons and the IC parameter Y may be dominated by Y_{EIC} . This will reduce the early X-ray flux emitted by these electrons since the X-ray flux recorded by XRT is $\propto (1+Y)^{-1}$ (e.g., eq. (6) of Fan & Piran 2006). For illustration, with $L_{ph} \sim 6 \times 10^{49} \text{ ergs}$ $\epsilon_{B,-2} E_{k,53} (t/400)^{-1.7} [(1+z)/2]^{1.7}$ for $400 \text{ s} < t < 10^4 \text{ s}$, we have $Y_{\text{EIC}} \approx 10(t/400)^{-0.7}$ (we have used Eq. [5] with $\Delta T/t = 1$ and with typical parameters). Depending on Y_{SSC} this reduces the X-ray flux by a factor of 3-10 and results in a slow declines as $t^{-0.5}$ rather than as $t^{-1.2}$. This provides a possible explanation to the puzzle of weak slowly declining X-ray flux observed by *Swift* in many GRBs (Nousek et al. 2006). Note, however, that this process requires a significant $\sim 10^{52} \text{ ergs}$ FUV emission.

3 POSSIBLE CANDIDATES OF THE PREDICTED SUB-GEV FLASHES

EGRET has detected more than 30 GRBs with sub-GeV photon emission (e.g., Schneid et al. 1992, 1995; Sommer et al. 1994; Hurley et al. 1994; Schaefer et al. 1998; González et al. 2003). In some events, which interest us here, the duration of the sub-GeV emission is longer than that of keV-MeV emission.

GRB 930131: The keV-MeV emission lasted $\sim 50 \text{ s}$ but two $\sim 100 \text{ MeV}$ photons were detected at 74 s and 99 s after the BATSE trigger (Sommer et al. 1994). Both the energy of photons and the count number seem to be consistent with the predictions of the far ultraviolet flare-forward shock interaction model.

GRB 940217: The sub-GeV emission lasted more than 5000 seconds and it included also a 18 GeV photon (Hurley et al. 1994). The spectrum in the energy range 1 MeV to 18 GeV, cannot be fitted with a simple power law (see Fig. 3 of Hurley et al. 1994). A new spectral component in the energy range larger than several tens MeV is needed. Possible models include the interaction of ultra-relativistic protons with a dense cloud (Katz 1994), SSC scattering in early forward and reverse shocks (Mészáros & Rees 1994) and an electro-

magnetic cascade of TeV γ -rays in the infrared/microwave background (Plaga 1995).

The long term strong X-ray flare detected in the high redshift burst GRB 050904 (e.g. Watson et al. 2006) hints that the long term sub-GeV emission of GRB 940217 may be explained as upscattering of FUV flare by the forward shock electrons (see also Wang et al. 2006). Of course we cannot tell now if there was an underlying long term FUV in GRB 940217, but its existence in other bursts makes this a viable model.

GRB 941017 has shown in addition to the typical GRB emission a distinct high-energy spectral component extending from $< \text{a few MeV}$ to $> 200 \text{ MeV}$. The high-energy component carried at least 3 times more energy than the lower energy component. The hard high energy component lasted 200 seconds, much longer than the low energy γ -ray emission that lasted $\sim 77 \text{ s}$ (González et al 2003). While various models have been put forward (Granot & Guetta 2003; Pe'er & Waxman 2004), the observed hard spectrum has not been well reproduced except in the neutral beam model (Dermer & Atoyan 2004) and the prompt γ -rays—reverse shock interaction model (Beloborodov 2005). It is also challenging to explain this rather hard spectrum with the FUV flares—forward shock interaction model discussed here.

In addition to GRB 041017, González et al. (2003) have found significant sub-GeV emission in other 25 bright GRBs. In these cases the high energy spectra are consistent with the single power law component observed by BATSE. This, of course, favors the internal shock synchrotron radiation model. Therefore, we are left in the EGRET era, with only two candidates (e.g., GRB 930131 and GRB 940217) of the predicted sub-GeV photon emission are available. The upcoming GLAST may be able to detect more events.

4 DISCUSSION AND SUMMARY

Bright X-ray flares have been detected a large group of *Swift* GRB afterglows. These flares have been attributed to late activity of the central engine. In most cases the peak energy is not known and it is possible that there is a significant far-ultraviolet component. These far-ultraviolet photons escape our detection because they are absorbed by the neutral hydrogen both in host galaxy and in our Galaxy before reaching Earth. We suggest here that these far-ultraviolet photons are IC upscattered by hot electrons within the shock that is ahead of them. This shock is driven by the blast wave produced by the ejecta that powered the initial GRB. This IC process will produce a strong sub-GeV burst what can be detected by upcoming *Gamma-Ray Large Area Telescope* (GLAST) satellite if the far-ultraviolet/X-ray flare is bright enough (the energy fluence $\mathcal{F} \sim 10^{-6} \text{ erg cm}^{-2}$). Alternatively, if most flare photons are in keV band rather than in far-ultraviolet band, the total number of photons being scattered (and the detected number of photons) is much smaller though the typical energy is much higher (Generally, they are in GeV-TeV energy range, see Wang et al. 2006). It is not easy to collect enough photons for significant detection.

We have also analyzed the sub-GeV detections of EGRET in view of this model. In some events (for example, GRB 930131, GRB 940217 and GRB 941017), the sub-GeV

photons are delayed. Out of these bursts, the spectrum of GRB 941017 is rather hard and it cannot be explained by this model. On the other hand the other two events seem to be consistent with the model. However, these sub-GeV photons could be generated in other scenarios (e.g., Mészáros & Rees 1994 Plaga 1995; Dermer & Atoyan 2004; Fan et al. 2005b). Without simultaneous soft X-ray observations we cannot confirm our model.

Finally, we point out that the extra cooling induced by continuous flux of FUV photons that pass through the forward shock reduces the X-ray flux produces by this shock front. Thus if the central engine does not turn off and gives out a significant emission of FUV photons several thousand seconds after the GRB, this emission will reduce the X-ray flux emitted by the forward shock at the beginning of the afterglow phase. This possibility provides an alternative explanation to the weak and slowly declining early X-ray light curve observed by *Swift* in many GRBs (Nousek et al. 2006). As this process involves emission of sub-GeV photons it could be tested by simultaneous observations of *Swift* and GLAST in the near future.

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